Status of the MUonE experiment

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Outline

- The muon g-2 and the hadronic contribution
- The MUonE experimental proposal
- Test Run 2021
- Conclusions
The muon g-2

Muon magnetic anomaly can be both measured and computed with very high precision, providing a stringent test of the Standard Model.

\[ a_\mu = \frac{g_\mu - 2}{2} \]

Latest measurement of \( a_\mu \)

Accuracy: 540 ppb

3.7\( \sigma \) discrepancy between theory and experiment

New experiment currently ongoing at Fermilab.

Aimed accuracy: 140 ppb

7\( \sigma \) if experimental value is confirmed.
Calculation of $a_\mu$ in the Standard Model

\[ a_\mu^{SM} = a_\mu^{QED} + a_\mu^{EW} + a_\mu^{had} \]

Calculated using perturbation theory

- $a_\mu^{QED} \sim 10^{-3}$
- $\delta a_\mu^{QED} \sim 10^{-12}$
- $a_\mu^{EW} \sim 15 \cdot 10^{-10}$
- $\delta a_\mu^{EW} \sim 10^{-11}$

Main contribution to the theoretical error

- $a_\mu^{HLO} = (693.1 \pm 4.0) \times 10^{-10}$


Perturbation theory cannot be used for the hadronic contribution (QCD is non perturbative at low energies)

The determination of $a_\mu^{HLO}$ needs to rely on experimental data
The hadronic contribution $\alpha_{\mu}^{HLO}$: time-like approach

Dispersion relation:

$$\alpha_{\mu}^{HLO} = \frac{\alpha_0^2}{3\pi^2} \int\limits_{4m^2_\pi}^{\infty} ds \frac{K(s)}{s} R(s)$$

$$R(s) = \frac{\sigma(e^+e^- \rightarrow \text{hadrons})}{\sigma(e^+e^- \rightarrow \mu^+\mu^-)}$$

$K(s) \sim 1/s$ smooth function

Measured at $e^+e^-$ accelerators

- Large fluctuations at low energies
- Merge measurements from different experiments
- Large systematic error

$$\delta\alpha_{\mu}^{HLO} \sim 4 \cdot 10^{-10} \sim 0.6\%$$
The hadronic contribution $a_{\mu}^{HLO}$: space-like approach

This method is completely independent from the time-like approach.

$$a_{\mu}^{HLO} = \frac{\alpha_0}{\pi} \int_{0}^{1} dx (1 - x) \Delta \alpha_{\text{had}}[t(x)]$$

$$t(x) = \frac{x^2m_\mu^2}{x - 1} < 0$$

Based on the measurement of $\Delta \alpha_{\text{had}}(t)$: hadronic contribution to the running of the electromagnetic coupling constant.

The MUonE experiment

Extraction of \( \Delta \alpha_{\text{had}}(t) \) from the differential cross section of the interaction

\[ \mu e \rightarrow \mu e \]

\[ \frac{d\sigma_{\text{data}}/dt}{d\sigma_{\text{MC}}^{\text{no VP}}/dt} = \frac{1}{|1 - \Delta \alpha_{\text{lep}}(t) - \Delta \alpha_{\text{had}}(t)|^2} \]

From theoretical calculation

To be measured

- A beam of 160 GeV muons allows to cover 87% of the \( \alpha^{HLO}_\mu \) integral
- Correlation between muon and electron angles allows to select elastic events and reject background (e\(^+\)e\(^-\) pair production)
- Boosted kinematics: \( \theta_\mu < 5 \text{ mrad}, \theta_e < 50 \text{ mrad} \)

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The experimental apparatus

Letter of Intent SPSC-I-252

M2 muon beam at CERN

$E_{\mu} = 160$ GeV

Beryllium target
1.5 cm thickness

Tracking system: 3 pairs of silicon strip detectors

$\times 40$

M2 $\mu$ beam
160 GeV/c

station #1 #2 #3 #k #N

ECAL

muon filter

$\mu$ chamber

$e$

$\mu$

$\sim 100$ cm
Achievable accuracy

40 stations + 3 years of data taking = Statistical accuracy on $a_\mu^{HLO}$: 0.3%

Competitive with the latest time-like accuracy

The big challenge of the experiment is to reach a comparable systematic accuracy

Systematic uncertainty of 10 ppm at the peak of the integrand function

- Longitudinal alignment (~10 µm)
- Knowledge of the beam energy (few MeV)
- Multiple scattering (~1%)
A Test Run with a reduced detector has been approved by SPSC, to validate our proposal.

Main goals:

- Pretracker +
- 2 MUonE stations +
- ECAL

- Confirm the system engineering.
- Monitor mechanical and thermal stability.
- Assess the detector counting rate capability.
- Check the DAQ system.
- Take data to extract $\Delta \alpha_{lep}(t)$. 

10 cm

100 cm
Location: M2 beam line at CERN

- Location: upstream the COMPASS detector (CERN North Area)
- Low divergence muon beam: $\sigma_x' \sim \sigma_y' \sim 0.3$ mrad
- Maximum rate: 50 MHz
- Spill duration $\sim 5$ s. Duty cycle $\sim 25\%$

Beam momentum

$\sigma_p/p \sim 3.75\%$

Beam spot: $\sigma_x \sim \sigma_y \sim 2.7$ cm

![Graph of beam momentum distribution](image1.png)

![Graph of beam spot distribution](image2.png)
Tracker: CMS 2S modules

Silicon strip sensors currently in production for the CMS-Phase2 upgrade

Two close-by strip sensors reading the same coordinate.

This provides background suppression from single-sensor hits and rejection of large angle tracks.

- **Thickness:** $2 \times 320 \, \mu m$
- **Pitch:** $90 \, \mu m \rightarrow \sigma_x \sim 26 \, \mu m$
- **Readout rate:** 40 MHz
- **Area:** $10 \, cm \times 10 \, cm$

Full angular acceptance with one module
Tracking station

- (x, y) layers tilted by 233 mrad, to improve single hit resolution.
  - Simulation studies show a resolution of ~10 µm.
- (u, v) layers to solve reconstruction ambiguities.

Stringent request: relative position within a station must be stable at 10 µm.

Low CTE mechanical structure: INVAR (alloy of 65%Fe, 35%Ni).
ECAL

Needed for particle ID and background rejection.

- 5x5 PbWO$_4$ crystals (CMS ECAL).
- 2.85x2.85 cm$^2$
- Total area: ~14x14 cm$^2$
- Readout: APD sensors.

TB2017 Simulation ($\sigma_x \sim 7\mu$m)
Tracker only

- Signal: elastic scattering
- Background: e$^+$e$^-$ pair production

TB2017 Simulation ($\sigma_x \sim 7\mu$m)
Tracker + ECAL > 1 GeV
• Test Run: read all data with no event selection.
• Information will be used to determine online selection algorithms to be used in the Full Run.
Sensitivity to $\Delta \alpha_{\text{had}}(t)$

Expected luminosity for the Test Run: $L = 5 \text{ pb}^{-1}$

$\sim 10^9$ events with $E_e > 1 \text{ GeV}$ ($\theta_e < 30 \text{ mrad}$)

We will be able to extract the leptonic running ($\Delta \alpha_{\text{lep}} \sim 10^{-2}$)

Initial sensitivity also to the hadronic running ($\Delta \alpha_{\text{had}} \sim 10^{-3}$)

$K = 0.137 \pm 0.027$

$\Delta \alpha_{\text{had}}(t) \sim -\frac{1}{15} K t$
Conclusions

- $a_\mu^{HLO}$ is the main source of uncertainty on the theoretical prediction of $a_\mu$.

- The new method proposed by the MUonE is independent and competitive with the traditional approach.

- The CERN SPS Committee has recently approved a Test Run of 3 weeks for the MUonE experiment in Fall 2021.

- The aim of the Test Run will be to verify the detector design and evaluate the analysis strategy.

- If the Test Run will confirm the goodness of our proposal, a Run with the full detector is envisaged in 2022-24.
Thanks for your attention!
BACKUP
\( E_{\text{beam}} = 150 \text{ GeV} \)

\[-0.143 \text{ GeV}^2 < t < 0 \text{ GeV}^2 \]

\[ t(x) = \frac{x^2 m^2_{\mu}}{x - 1} < 0 \]

\[ 0 < x < 0.932 \]
Correlation curve \((\theta_e, \theta_\mu)\)

\[
\sin \theta_\mu = \frac{p'_e \sin \theta_e}{p'_\mu} = \sin \theta_e \sqrt{\frac{E^2_e(\theta_e) - m^2_e}{[E_\mu + m_e - E_e(\theta_e)]^2 - m^2_\mu}}
\]

It allows to select signal events and reject the background.
Extraction of $\Delta \alpha_{\text{had}}(t)$

$\Delta \alpha_{\text{had}}(t) \lesssim 10^{-5}$

$\theta_e \gtrsim 30$ mrad

No sensitivity to $\Delta \alpha_{\text{had}}(t)$ in this region
"Lepton-like" parameterization

\[ \Delta \alpha_{\text{had}}(t) = K M \left\{ -\frac{5}{9} - \frac{4}{3} \frac{M}{t} + \left( \frac{4}{3} \frac{M^2}{t^2} + \frac{M}{3t} - \frac{1}{6} \right) \right. \frac{2}{\sqrt{1 - \frac{4M}{t}}} \ln \left| \frac{1 - \sqrt{1 - \frac{4M}{t}}}{1 + \sqrt{1 - \frac{4M}{t}}} \right| \left. \right\} \]

Inspired from the analytical function of the leading order leptonic running

\[ K = \text{related to } \alpha_0 \text{ and the electric charge of the lepton in the loop (and also colour charge for quarks)} \]

\[ M = \text{related to the squared mass of the particle in the loop} \]

It allows to extrapolate \( \Delta \alpha_{\text{had}}(t) \) also in the region which is not accessible by kinematics \((x > 0.932)\).
Select only particles above a certain transverse momentum $p_t$ for the 40 MHz readout.

Correlation window: ±7 strips.
Window offset = 0.
Max cluster width = 4 strips.

Stub information: position of the cluster in the seed layer + distance between position of correlation cluster and seed cluster (bend)
The single hit resolution is defined as the st.dev. of the distribution

\[ x_{true} - x_{stub} \]

\[ x_{true} = \frac{x_{seed} + x_{corr}}{2} \]

\[ x_{stub} = \frac{x_{seed} + x_{corr}}{2} \]

\[ x_{true} = \mu \text{ position in the middle of the 2S module} \]

\[ x_{true}^{exit \ (corr)} \text{ and } x_{true}^{entry \ (seed)} \text{ taken from Geant4} \]

\[ x_{true}^{entry \ (seed)} \]

\[ x_{true}^{exit \ (corr)} \]
Single hit resolution - non tilted geometry

\[ \sigma_{1hit} = 22.4 \mu m \]
Single hit resolution - tilted geometry

Tilted geometry: improvement in resolution due to two different effects:

1) charge sharing: energy deposition of particles in the Si is shared among neighbouring strips
2) effective staggering: tilting a 2S module by 25 mrad is equivalent to stagger the two sensors by \( \frac{1}{2} \)pitch

Optimal point:
- tilt angle: 233 mrad
- threshold: 6σ

Resolution for 150 GeV muons:
\[ \sigma_{1hit} = 8.0 \mu m \]
Multiple scattering: results from TB2017

Multiple scattering effects of electrons with 12 and 20 GeV on Carbon targets (8 and 20 mm)

Main goals:

- to determine a parameterization able to describe also non Gaussian tails
- to compare data with a GEANT4 simulation of the apparatus
Results show a \( \sim 1\% \) agreement between data and MC for the Gaussian core.

\[ f_e(\delta \theta_e^x) = N \left[ (1 - a) \frac{1}{\sqrt{2\pi} \sigma_G} e^{-\frac{(\delta \theta_e^x - \mu)^2}{2\sigma_G^2}} + a \frac{\Gamma(\frac{\nu+1}{2})}{\sqrt{\nu\pi} \sigma_T \Gamma(\frac{\nu}{2})} \left( 1 + \frac{(\delta \theta_e^x - \mu)^2}{\nu \sigma_T^2} \right)^{-\frac{\nu+1}{2}} \right] \]

\[ \mathbf{p} = [N, a, \mu, \sigma_G, \nu, \sigma_T] \]

\( \chi^2/\text{ndf}=237.9/194 \)